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Resonances in heavy ion reactions—highly deformed nuclear shapes

M A Eswaran
Nuclear Physics Division, Bhabha Atomic Research Centre,
Bombay-400 085, India

Abstract : The study of the intermediate width resonances observed in the energy dependence of cross sections of heavy ion reactions is one of the significant lines of investigations in nuclear physics In earlier years there have been explanations of such heavy ion resonances in terms of dynamical models in which these resonances are viewed as being a consequence of both weak absorption and existence of pockets in the interaction potential of two ions In recent years experimental investigations have found evidences to infer that the resonances might be manifestations of shape isomeric states of compound system produced in super deformed second well in the potential energy surfaces. In this talk recent results of such investigations of very large nuclear deformations at high excitations in light nuclei are presented both from literature as well as from our studies with Pelletron accelerator at Bombay on ^{28}Si through resonances in the ^{16}O + ^{12}C system

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The resonant behaviour in heavy ion reactions was first observed over thirty years ago in the excitation functions of the ^{12}C + ^{12}C reaction [1]. The energy dependence of the angle integrated yields of protons, neutrons alpha particles and gamma rays in these reactions showed correlated peaks [1]. Similar behaviour was also observed in a wide range of nuclear systems ranging from *s–d* shell (^{12}C + ^{12}C) to the *f–p* shell (^{18}Si + ^{28}Si) [2,3]. The experimental identification of these resonances which are in the energy region of 20 to 70 MeV excitation have to be carefully done since they have to be differentiated from the fluctuating cross sections due to the effect of overlapping levels [4,5]. The resonances were also found to exist well above the coulomb barrier and were proven to decay nonstatistically in particle channels. These observations were first interpreted in terms of the new class of nuclear states with large partial widths for decaying into fragments of comparable mass which led to visualising them as fission like configurations.

The excitation energies where resonances in heavy ion reactions are observed are typically of the order of 20 to 70 MeV with corresponding level densities of 10^2 to 10^6 MeV^{-1} for systems ^{12}C + ^{12}C to ^{28}Si + ^{28}Si. Hence it can be surmised that certain extraordinary features are playing a role to keep a resonant state from dissolving into the complex background of underlying nuclear levels.

In earlier years, the molecular concept of heavy ion resonances was developed and it was particularly based on the fact that resonances in given composite systems follow a rotations-like formula (*i.e.*) that their median energies for given angular momentum values can be accounted for by an expression of the type

$$E = E_o + \alpha . J (J + 1), \tag{1}$$

typical of a rigid rotor [6].

A notable feature is that the values of the constants E_o and α in the equation (1) obtained by fitting experimental resonance data in an E *vs* J $(J + 1)$ plot, correspond to rotational molecular parameters. In fact, E_o is roughly equal to $E_B + E_C$ with E_B the binding energy of the projectile + target in the composite system and E_C the projectile + target Coulomb barrier energy while α can be expressed as $\hbar^2 / 2^I$ with an effective moment of inertia deduced from the average slope of resonance data. The values of I obtained in this way are very close to values of moment of inertia of two touching rotating nuclei having projectile and target masses respectively.

Several schematic models based on the quasi-molecular concept outlined above were proposed for the observation of heavy ion resonances. These are (1) The orbiting cluster model [6], (2) The model of level densities at grazing angular momenta [7], (3) The model of weak absorption into direct channels [8], (4) The effective barrier model [8].

All these schematic models share the following common concepts. According to these, the resonance occurrence in heavy ion reactions is related to high spin configurations arising at grazing collisions and it will occur in those heavy ion entrance channels in which these configurations are not damped strongly. Resonances will occur preferably in those heavy ion systems which have sufficiently low binding energy in a given composite system and largest grazing moment of inertia.

The difference in the resonant behaviour between the alpha-particle type'systems and others have also been noticed. For example the elastic scattering data [9] for ^{28}Si + ^{28}Si and ^{24}Mg + ^{24}Mg data show prominent resonance structures, the data of ^{28}Si + ^{30}Si and ^{30}Si + ^{30}Si show no real signs of structure. Similar observations are noted in the case of inelastic and transfer cross sections also. For the systems which are not alpha-particle type, not only the resonant structures are absent mostly but also the total large angle cross sections are lower.

Even though many of the features observed in this field of heavy ion resonances are not fully understood, there is a speculation, consistent with the experimental observations, which comes from the visualisation of resonances as shape isomers [9]. It has been noted that Nilsson-Strutinsky type calculations by Leander and Larsson [10] and other authors predict the existence of super-deformed second minima in the potential energy surfaces for $4n$ nuclei from ^{16}O to ^{44}Ti. In these calculations axially asymmetric and reflection asymmetric shape degrees of freedom are included. Such secondary minima are well known in actinide nuclei where they are responsible for fission isomers. Hence, it can be conjectured that the resonances seen in these much lighter nuclei are akin to fissioning shape isomers. The appearance of resonances mostly in alpha-particle type nuclei can be understood as an enhancement of the deformed shell effects responsible for second minima in nuclei with $N = Z$. There is near identity of proton and neutron orbitals in this mass region with a consequent enhancement of any shell effects where both are filled equally.

Specific experimental evidence for this explanation of the resonances in terms of shape isomers has come from the observations of selective alpha particle decay of $^{12}C + {}^{12}C$ resonances to excited ^{20}Ne rotational bands. Ledoux [11] *et al* have measured excitation functions for the reaction $^{12}C\,(^{12}C, \alpha)\,^{20}Ne$ in the energy range $E_{c\,m} = 14$ to 40 MeV and found that several prominant intermediate structure resonances which are correlated with resonances in other channels decay to few special ^{20}Ne excited states some of which are known to have $8p$–$4h$ configurations, with reduced widths, an order of magnitude greater than those for the ^{20}Ne ground state band.

Such evidence for shape isomeric nature of resonances in ^{28}Si have recently been obtained in our work [12] with BARC-TIFR Pelletron Accelerator at Bombay where excitation functions have been measured in the reactions $^{12}C(^{16}O, \alpha)\,^{24}Mg$ and $^{12}C(^{16}O, {}^{8}Be)\,^{20}Ne$ leading to several excited states upto 22 MeV in ^{24}Mg and 9 MeV in ^{20}Ne. Three surface barrier ΔE–E particle identifier detectors were used at three different angles with respect to the beam in the scattering chamber. Since ground state of ^{8}Be is unbound by 92 KeV and decays into two alpha particle the identification of ^{8}Be in the ΔE–E telescope is achieved by having large enough solid angle for detection of both the decay alpha particles in the detector. The effective detection efficiency has to be numerically calculated. An example of the alpha spectrum and ^{8}Be spectrum recorded in these reactions are shown in Figure 1. Several excitation functions leading to 19 different states in alpha channel and 5 different states in ^{8}Be channel have been recorded from $E(^{16}O) = 60$ to 90 MeV. From cross correlation analysis two resonances at $E_{(c.\,m)} = 26.9$ and 29.5 MeV corresponding to excitation energies in ^{28}Si at $Ex = 43.7$ and 46.2 MeV have been identified. These two resonances are well correlated in alpha and ^{8}Be channels and decay by ^{8}Be emission to known superdeformed $8p$–$4h$ states around 7.2 MeV in ^{20}Ne and not to the ground state

(Figure 2). This provides evidence for the resonances to be having intrinsic configurations of shape isomeric states in the shell model secondary minimum in ^{28}Si with selective ^{8}Be

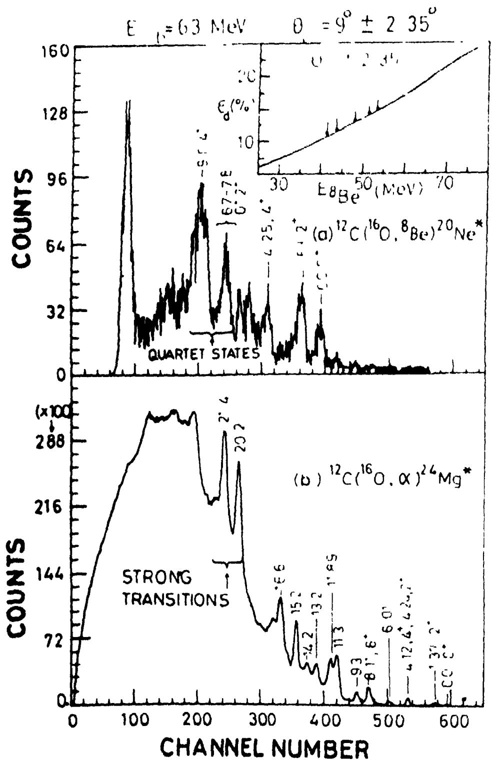

Figure 1. (a) The ^{8}Be spectrum recorded in the ΔE-E detector telescope from the reaction ^{12}C (^{16}O, ^{8}Be) ^{20}Ne at E (^{16}O) = 63 MeV. The numbers above the peaks denote the excitation energies in MeV of states in ^{20}Ne The inset shows the detection efficiency ε_d of the ^{8}Be detector, as a function of energy of ^{8}Be and the arrows indicate the energies corresponding to the marked peaks in the spectrum. (b) The alpha spectrum recorded in the same telescope from the reaction ^{12}C (^{16}O, α) ^{24}Mg. The dotted line indicates the smooth continuum which was substracted for evaluation of excitation function measurements.

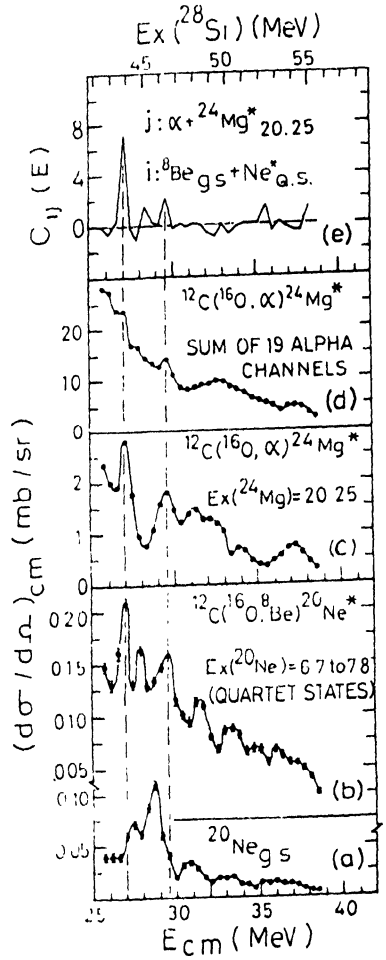

Figure 2. Selected excitation functions . (a) ^{8}Be channel in the reactions ^{12}C (^{16}O, ^{8}Be) ^{20}Ne leading to ground state of ^{20}Ne. (b) ^{8}Be channel leading to quartet states near 7.2 MeV in ^{20}Ne (c) Alpha channel leading to 20.25 MeV state in ^{24}Mg in the reaction ^{12}C ($^{16}O,\alpha$) ^{24}Mg. (d) Sum of 19 alpha channels in the reaction ^{12}C (^{16}O, α) ^{24}Mg. (e) Cross correlation coefficient between excitation function shown in (b) and (c).

decay being transitions to states of related configurations in ^{20}Ne as expected from the potential energy calculations.

The lower resonance at excitation of 43.7 MeV has a weak branch decaying by α emission to ground state of ^{24}Mg. Angular distribution of alpha in this channel was determined which enabled assignment of spin of 14 to this resonance (Figure 3) from the fit

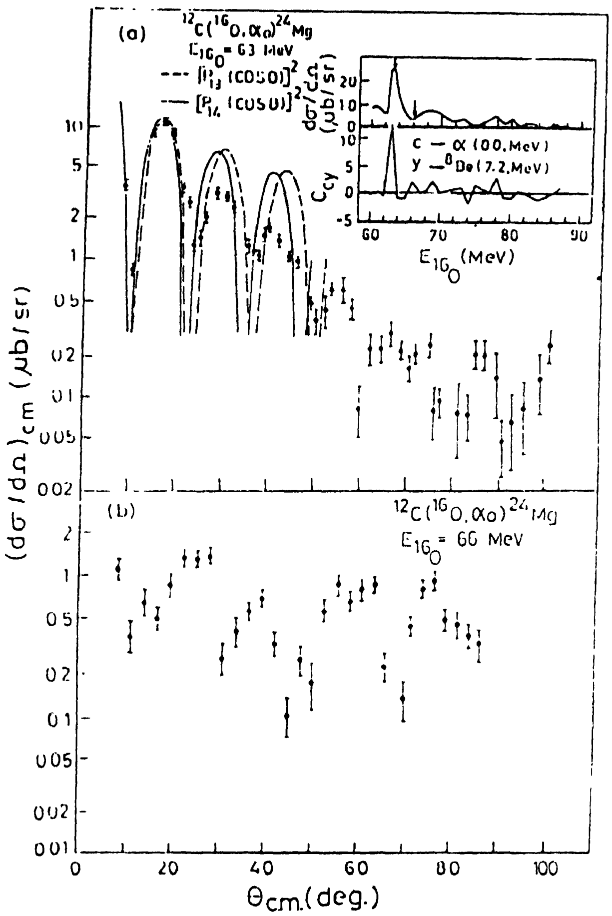

Figure 3(a). Angular distribution for the reaction ^{12}C (^{16}O, α) ^{24}Mg at "ON" resonance energy of E (^{16}O) = 63 MeV. The data points are shown by closed circles with statistical error bars. The $[P_l (\cos\theta)]^2$ are also shown. The inset shows the excitation function for this reaction indicating resonance at E (^{16}O) = 63 MeV and cross correlation function $C_{\alpha y}$ for correlation with the ^{8}Be channel leading to the 7.2 MeV state of ^{20}Ne. (b) Angular distribution for the same reaction at "OFF" resonance energy of E (^{16}O) = 66 MeV.

of $[P_{14} (\cos\theta)]^2$ to the data. The spin value is found to be 4 units less than the l-grazing value of 18 in the incident ^{16}O + ^{12}C channel in this reaction but equal to l-grazing value of 14 in the exit, α + ^{24}Mg channel, as calculated from optical model potential [12].

These two resonances were also found to decay strongly to the 20.2 and 21.4 MeV states in ^{24}Mg with cross sections much larger than expected from statistical model expectations. To investigate the nature of these states near 20 MeV region in ^{24}Mg by the study of their α-decay to various states in ^{20}Ne, the alpha-alpha coincidence measurements were also made by us [13] in the reaction $^{12}C(^{16}O, \alpha 1)$ $^{24}Mg^*$------$\alpha 2$ + $^{20}Ne^*$ at 63 MeV beam energy corresponding to the resonance at 43.7 MeV in ^{28}Si. Form the spectra of $\alpha 1$ at 0° recorded in coincidence with the $\alpha 2$ at various angles leading to the first three states of ground state band namely 0^+, 2^+, 4^+, and the 7.2 MeV, 0^+ $8p$–$4h$ quartet states of ^{20}Ne, double differential cross section in centre of mass system *i.e.*, $(d^2\sigma/d\Omega^2)$ c.m. were calculated. Figure 4(a–d) illustrate the $\alpha 1$–$\alpha 2$ coincidence cross section against the $\alpha 1$-energy for $\alpha 2$ feeding the 7.2 MeV, 0^+ ; g.s., 0^+ ; 4.24, 4^+ ; and 1.63, 2^+ states of ^{20}Ne

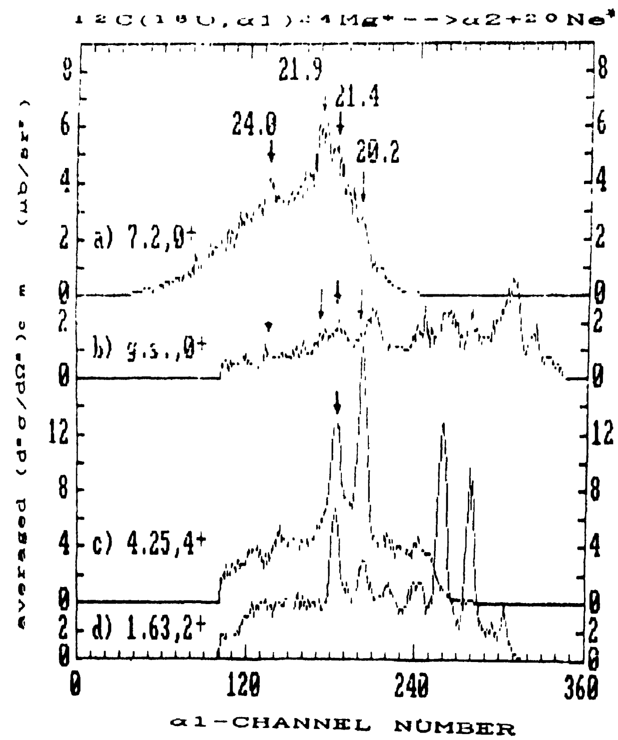

Figure 4. (a) to (d) show $\alpha 1$–$\alpha 2$ coincidence cross section plotted against $\alpha 1$-energy for $\alpha 2$ feeding the 7.2 MeV 0^+, g.s.0^+, 4.24 MeV 4^+ and 1.63 MeV 2^+ states for ^{20}Ne respectively vertical arrows indicate the various excited states of ^{24}Mg in MeV (see text).

respectively. The vertical arrows indicate the various excited states of ^{24}Mg in MeV. These spectra indicate the α-decay mode of the 19 to 25 MeV region of excitation of ^{24}Mg fed from the resonance in ^{28}Si at 43.7 MeV.

From these data it could be deduced that the states in 20 to 24 MeV region of ^{24}Mg preferentially decay to the $8p$–$4h$ 7.2 MeV 0^+ state rather than to the ground state of ^{20}Ne. Hence these states in ^{24}Mg have much more structural overlap with the 7.2 MeV superdeformed $8p$–$4h$ state than with the ground state of ^{20}Ne [13].

The 7.2 MeV $8p$–$4h$ state of ^{20}Ne is associated with the $(0p)^{-4}$ $(sd)^8$ configuration having deformation parameters $\varepsilon = 1.17$ and $\nu = 50°$[10]. From the present data we could conjecture that the 43.7 MeV resonance in ^{28}Si corresponds to potential energy minimum with configuration $(0p)^{-4}\,(sd)^{12}\,(fp)^4$ with $\varepsilon = 1.35$ and $\nu = 60°$ based on the calculation of Leander and Larsson [10].

Figure 5 shows the energy level diagram of the decay modes of the resonances and also the calculation of Leander and Larsson [10] for the potential energy surface of ^{28}Si and

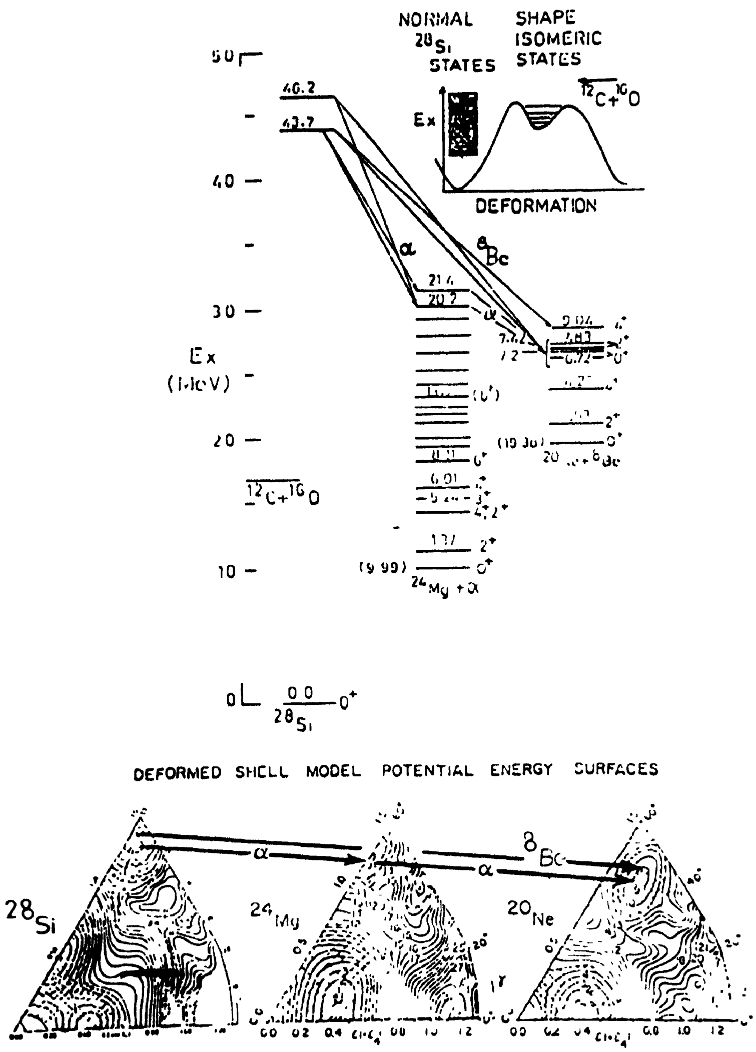

Figure 5. Energy-level diagram showing two resonances in the system ^{12}C + ^{16}O identified in the present work. The strong correlated decay of the resonances in the α and ^{8}Be channels are shown in the figure are those for decay to which the excitation functions have been measured in the present work. The lower portion of the figure shows potential energy surfaces for ^{28}Si, ^{24}Mg and ^{20}Ne from the deformed shell model calculations of Leander and Larsson (Ref. 10). Thick arrows connecting the shape isomeric configurations of ^{28}Si, ^{24}Mg and ^{20}Ne by ^{8}Be and α decay modes are based on the observations in the present work.

^{24}Mg and ^{20}Ne. Our inferences of the minima in ^{28}Si, ^{24}Mg and ^{20}Ne corresponding to resonances in ^{28}Si and states fed in ^{24}Mg and ^{20}Ne from the resonances are also shown in the figure.

Recently an experiment has also been reported by Wuosmaa *et al* [14] which provide evidence for identification of six alpha particle linear chain configuration in ^{24}Mg. They have observed a strong peak in the excitation function for the inelastic scattering reaction ^{12}C (^{12}C, ^{12}C (O_2^+)) ^{12}C (O_2^+) at an energy of E_{cm} = 32.5 MeV. This is interpreted as arising from a very highly deformed 6α-particle chain configuration at excitation energy of 46.4 MeV in ^{24}Mg. This has also been interpreted by Rae *et al* [15] as a new type of resonance which is formed coherently from nearby degenerate resonances with different *l* values corresponding to an approximate shape eigenstate. Nilsson-Strutinsky type calculations [10] and also cluster model calculations of Merchant and Rae [16], also predict potential energy minima corresponding to such exotic states of very large deformations.

In conclusion, much more experimental and theoretical work is necessary for a complete understanding of this phenomenon of heavy ion resonances which has its basis in nuclear structure in the region of excitation energy and angular momentum where it might have been suspected that all nuclear structure effects would have vanished. The full understanding will naturally involve both the theories of reaction mechanism and nuclear structure at high excitation energy and angular momentum and this will significantly enhance our konwledge of the nucleus.

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